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## PIONEERING SCRAMJET DEVELOPMENTS BY ANTONIO FERRI

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### PROLOGUE

"I would like to make the following statement: The existing technological ability and scientific background accumulated in many years of work will be lost if a small but continuing effort in this field is not maintained. Resumption of work in air-breathing engines at a later date would require a much larger effort."

Antonio Ferri, 1960, "Possible Directions of Future Research in Air-Breathing Engines," AGARD Combustion and Propulsion Colloquium, Pergamon Press Ltd., London, England.

"We now have 5000 people working on the National Aero-Space Plane program"

Robert Barthelemy, 1990, address to participants in the 8th Semi-annual NASP Technology Symposium, Monterey, California.

### INTRODUCTION

This presentation summarizes the concept of a diffusive burning supersonic combustion ramjet engine (scramjet) envisioned by Antonio Ferri and highlights some of the salient technologies developed at GASL, PIBAL and NYU under his direction.

Although true paternity of the scramjet engine may never be conclusively determined, it is clear from the published literature that the concept of a ramjet engine that burned the fuel in an airstream which entered the combustor supersonically occurred more-or-less independently to a small group of researchers between 1947 (References 1 and 2) and 1960 (References 3 and 4). Two approaches were envisioned: one used a detonation wave to burn the fuel and the other, first proposed by Ferri, used a diffusive (i.e. mixing controlled) process that was (ideally) shock-free. The subsonic burning ramjet, the supersonic detonative-burning scramjet and the diffusive-burning scramjet are compared schematically in Figure 1. The detonation wave engine concept is clearly first attributable to Maurice Roy (Reference 1) but the recorded discussion following his 1959 paper indicates that the first

experimental demonstrations were carried out in U.S. industrial and university research labs in the late 1950's, and that Ferri's experimental achievement of diffusive supersonic combustion carried out at the same time, also in the U.S., was, at very least, the first such demonstration having development of an orbit-capable aircraft engine as its goal (Reference 5). Inclusion of the diffusive-burning supersonic combustion ramjet in a "composite" (i.e. multi-stage) system was also envisioned from inception of the engine concept (Reference 6).

Ferri conducted most of his basic scramjet research activities in the Aerospace Laboratories he built at the Polytechnic Institute of Brooklyn (PIBAL) and later at New York University (NYU), and directed the technology development, systems development and application studies employing the resulting technology to supersonic and hypersonic cruise and orbit-capable aircraft at General Applied Science Laboratories, Inc. (GASL). The first serious attempt to design and build a SSTO aircraft employing a composite turbojet, ramjet, scramjet and rocket system was conducted in cooperation with Republic Aviation, as part of the Air Force's original Aero-Space Plane project. As described in the Republic Aviation News issue of September 9, 1960, the aircraft would employ four hydrogen-fuelled J-58 type turbojet engines and four ramjet engines that transitioned to supersonic combustion for the Mach 7 to 25 range, have a gross take-off weight of 400,000 lbs and a payload of 20,000 lb. The Air Force program was terminated about five years later, and while none of the competing aircraft designs could achieve the SSTO objective, it is generally agreed that the Republic design with its heavy dependence on airbreathing propulsion to orbit was the most promising. Concurrently with the Aero-Space Plane program, the Air Force sponsored several scramjet engine development programs. An Air Force press release dated November 12, 1964, announced the "first successful demonstration of internal thrust from a scramjet engine." "The tests were conducted at General Applied Science Laboratories, Inc. Westbury, New York, under the supervision of Dr. Antonio Ferri, GASL President."

## TECHNICAL HIGHLIGHTS

"From an operational point of view, the ideal vehicle for space investigations is probably a vehicle that is able to take off as an airplane with low accelerations, can accelerate gradually to orbital speed along a trajectory that can be controlled in time and position, can carry a large payload, and can re-enter, land, and be used again for successive missions." With those introductory remarks, Ferri went on to describe a preliminary study of such an orbit-capable aircraft in Reference 3. He proposed use of hydrogen-burning turbojet engines to accelerate from take-off to Mach 3, followed by ramjet engines to "high Mach numbers" (around 8 to 10) and then diffusive burning scramjets to orbit. He dismissed use of detonative combustion due to the variable geometry requirements. Indeed, he recognized that the specific impulse (Isp) advantage of the ramjet/scramjet could be easily offset by the weight of a variable geometry inlet system. The desire to achieve the required inlet starting characteristics at low supersonic Mach numbers and the required compression at high Mach numbers with a fixed geometry engine became the hallmark of Ferri's scramjet work. Toward this end, his inlet designs became characteristically three-

dimensional and employed the concept of "thermal compression" to achieve the goal of fixed geometry.

Without regard to the details of the design, the first paper presented a series of scramjet engine parameters and performance characteristics that varied relatively little in subsequent studies. What did change is the depth of the technology base and design effort to support the performance estimates. The original vehicle layout is shown in Figure 2, together with the weight and payload. Ferri noted that a doubling of structural weight would triple the take-off weight, perhaps more closely resembling the Republic design. The key engine design parameter is the combustor inlet Mach number, which is shown in Figure 3. Further details of the inlet and combustor were presented in later papers. The initial estimates of specific impulse in the scramjet mode from this study are presented in Figure 4. Ferri's aircraft design also placed more emphasis on maximizing the inlet capture area than the Republic design. The figure of 100 sq.ft. of inlet stream tube capture area pertains to Figure 5, which shows the engine thrust levels. Estimates of thrust minus drag then yielded the acceleration potential shown in Figure 6.

A concerted effort to provide the technology base for these performance estimates then followed at PIBAL (Reference 7). Notable accomplishments included the development of pioneering CFD capabilities based on the Method of Characteristics and Parabolized Thin-Layer Navier Stokes solvers with coupled finite-rate chemical reactions, experimental surveys of supersonic hydrogen-air mixing layers and comparisons with theory to "tune" the postulated eddy viscosity models, and conduct of diffusive supersonic combustion experiments with direct and schlieren flow visualization.

In a coordinated effort at GASL, Ferri directed the construction of a combustion-driven shock tunnel in which the first measurements of supersonic combustion of hydrogen in a pulse type test facility were made. These measurements became the basis for the first correlation of ignition delay time for hydrogen-air mixtures at representative scramjet conditions. He also built a hydrogen combustion heated vitiated air wind tunnel with Mach 3 to 8 simulation capabilities to test ramjet and scramjet engine concepts, which is still in daily use.

The results of these technology development studies as well as updated system studies were summarized in Ferri's 1964 Lanchester Memorial Lecture (Reference 8) and in an AIAA survey article (Reference 9). Of interest is the capture area schedule and total pressure recovery calculated for a fixed geometry inlet in the Mach 4 to 24 range shown in Figure 7. The inlet design is "similar to that" of Reference 3. Spillage drag and skin friction drag were included in the calculated performance shown in Figure 8. It was also pointed out in this paper that a fairly low trajectory must be flown to have sufficient air capture rate and dynamic pressure to be able to obtain an adequate thrust margin for acceleration, indicated in Figure 9 as the "acceleration corridor." Associated with the high dynamic pressure is a high heat transfer rate and consequently a high temperature (2000°R) for the hydrogen fuel being used as a regenerative coolant for the structure. On the positive side,

a significant amount of thrust is derived from expanding the hot hydrogen to supersonic axial velocity through the fuel injectors. On the other hand, at some suborbital speed (depending on the trajectory and the vehicle design) the fuel flow rate required to cool the structure begins to exceed the stoichiometric rate required for acceleration. In Ferri's design, this occurred at about Mach 22, as shown in Figure 10, with the inlet and nozzle surfaces being the primary contributors to the cooling problem. Performance trade-offs associated with fuel-air equivalence ratio and other engine component parameters are discussed in the paper. Although the quantitative results for engine performance may not be consistent with current technology, all the basic aerophysics and engine design considerations discussed in this paper are still pertinent today.

While not explicitly covered in this presentation, the subject of thermal compression is well worth noting. The basic concept was to use the addition of fuel mass and the concomitant release of heat to accomplish a portion of the inlet compression process, in preference to variable inlet contraction. The fluidic control system should be substantially lighter than mechanical systems for geometric variations of the inlet surfaces. The concept was originally tested at relatively low supersonic Mach numbers where the low momentum of the fuel and large pressure increases associated with combustion conspired to make control difficult. However, at the higher (hypersonic) Mach numbers where scramjet combustor tests are currently being conducted in pulse facilities, the occurrence of thermal compression is frequently evident in the data, and the conditions are far more favorable to its exploitation.

## EPILOGUE

Ferri's last review of scramjet technology was presented at the AIAA Third Annual Meeting in 1966 (Reference 10). He left GASL in 1967, and in 1968 moved from PIB to NYU. He continued his research efforts in scramjet combustion at NYU under NASA sponsorship. In 1972, Ferri and a group of colleagues rejoined GASL. Unfortunately, he died of a heart attack in 1975, about a decade before the current resurgence of interest in scramjet engines and SSTD aircraft began. His close colleague, Mr. Ernest Sanlorenzo, who joined Ferri (and the second author) at GASL in 1956, devoted a large part of his career to pursuing scramjet technology, and was originally scheduled to give this presentation, also died of a heart attack in January 1992, while managing the NASP ramjet/scramjet tests at GASL. The remaining "corporate memory" of Ferri's ideas for the design of scramjet engines, not reported in the literature but conveyed through lively technical discussions, resides with three people at GASL (besides the authors) and a few people scattered throughout the aerospace community.

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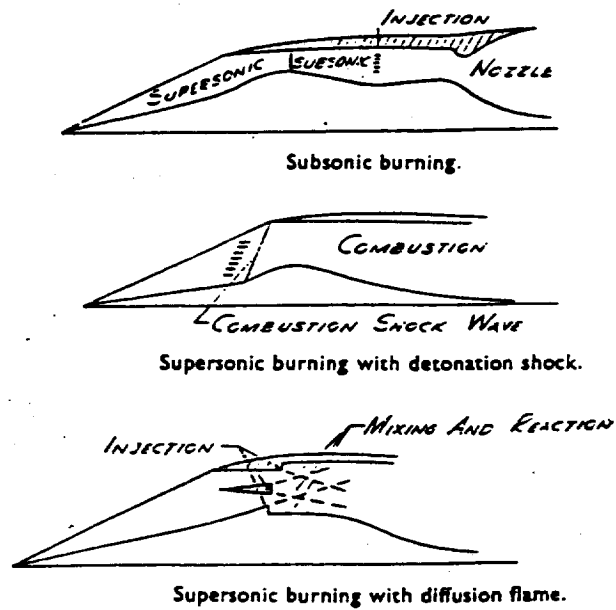


Figure 1. Schematic Representations of Subsonic Burning Ramjet, Detonative Burning Scramjet and Diffusive Burning Scramjet

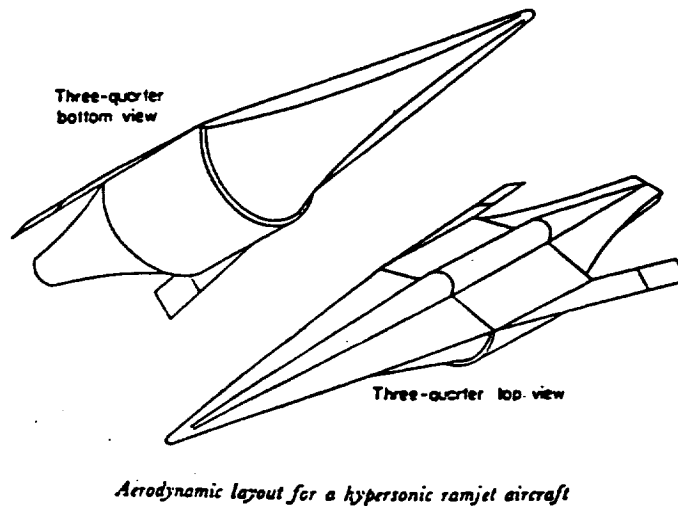
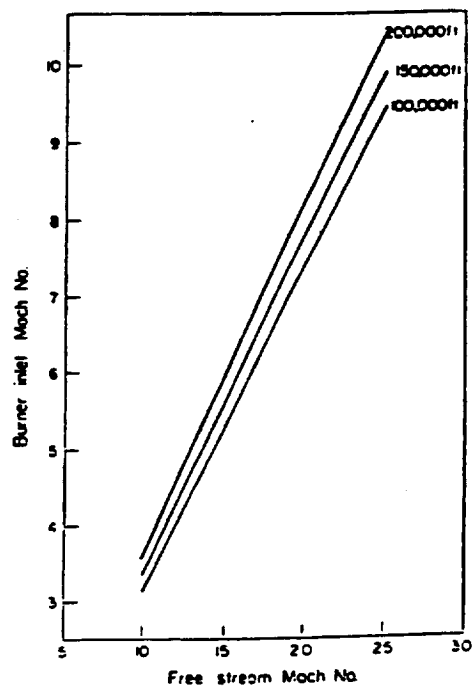


Table 1

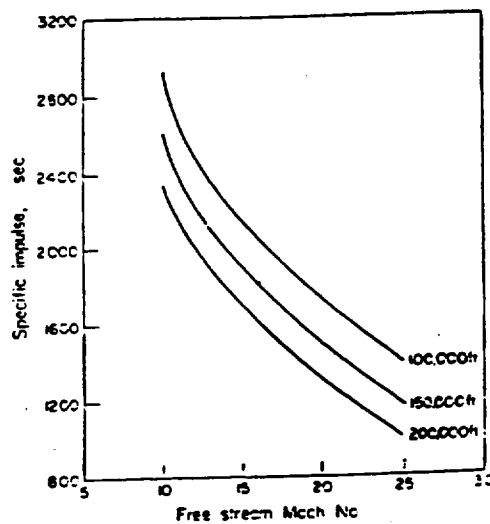
Initial weight	130,000 lb
Empty weight in orbit	50,000 lb
Payload in orbit	10,000 lb

Figure 2. Perspective Drawings of Ferri's 1960 Air-Breathing SSTO Aircraft and Estimated Weights



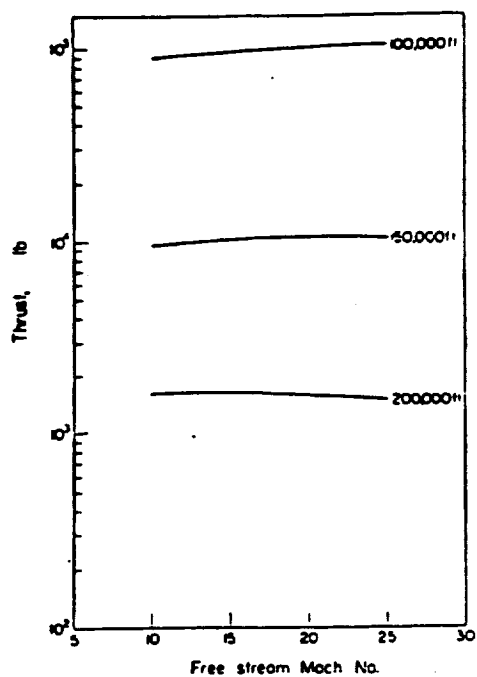
*Ramjet burner inlet Mach number*

Figure 3. Scramjet Combustor Entrance Mach Number Schedule (1960)



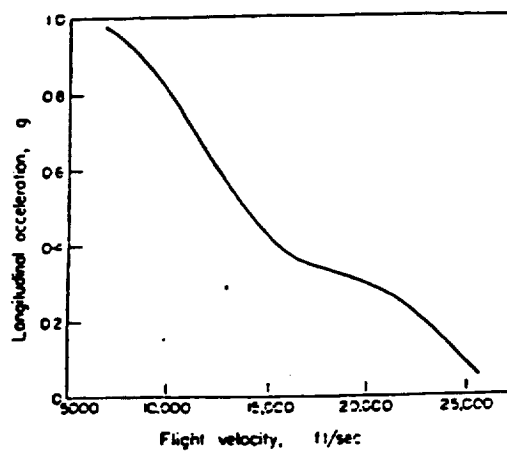
*Ramjet specific impulse with supersonic burning hydrogen fuel*

Figure 4. H<sub>2</sub>-fuelled Scramjet Specific Impulse Estimates (1960)



*Ramjet thrust with supersonic burning; free stream capture area 100 ft<sup>2</sup>; hydrogen fuel*

Figure 5. H<sub>2</sub>-fuelled Scramjet Thrust Estimates (1960)



*Typical acceleration capability for a hypersonic ramjet aircraft*

Figure 6. Acceleration Capability of Ferri's 1960 SSTO Aircraft

# **INITIAL CONDITIONS FOR FIXED-GEOMETRY ENGINE**

$A_1/A_0'$  (burner entrance inlet areas) = 0.02.

A. Inlet performance.

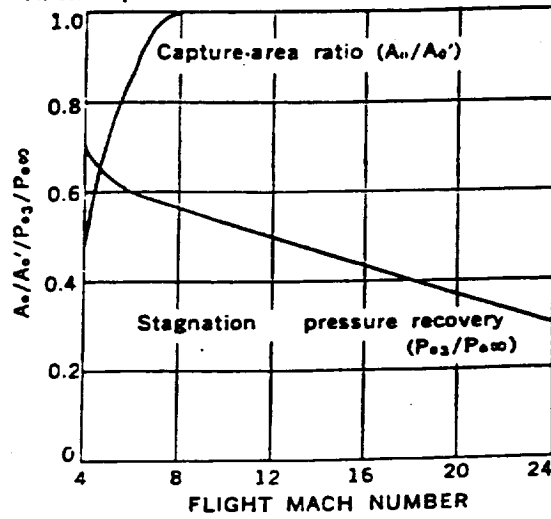


Figure 7. Performance of Ferri's Fixed Geometry Inlet (1964)

## **ENGINE PERFORMANCE FOR FIXED-GEOMETRY ENGINE**

$A_1/A_0'$  (burner entrance area/inlet area) = 0.02;  
nozzle exit area/inlet area = 1.2;  $P_\infty$  = free-stream pressure.

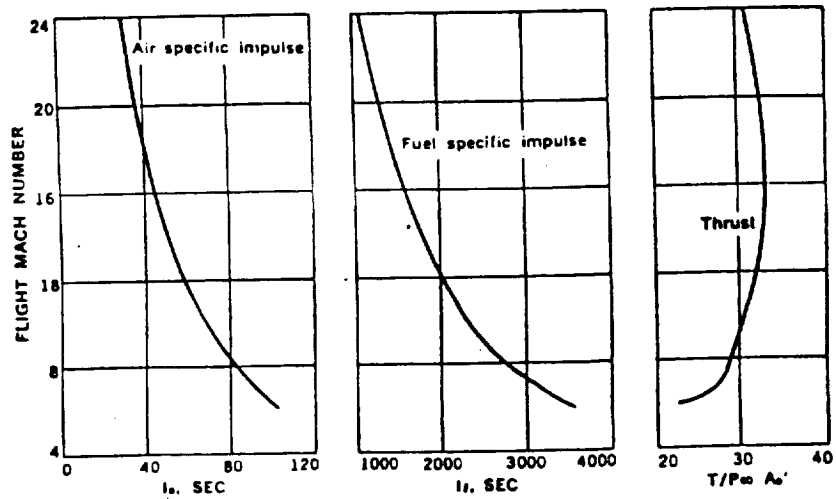


Figure 8. Performance of Ferri's Fixed Geometry Scramjet Engine (1964)

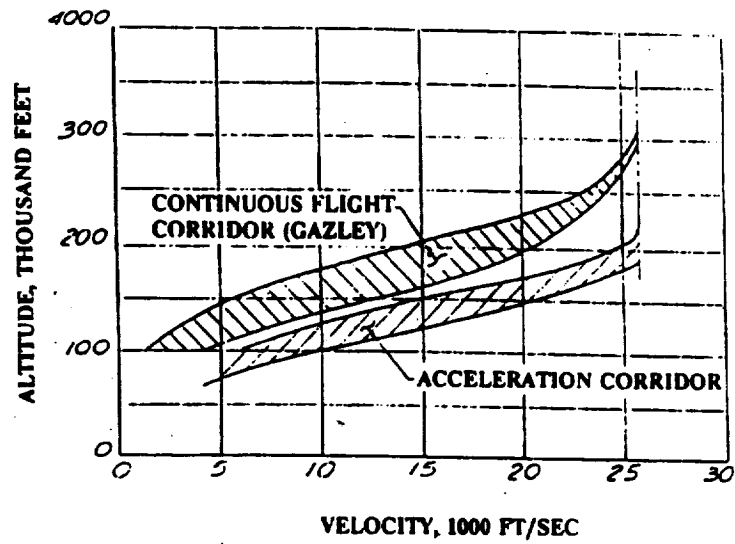


Figure 9. Comparison of Ferri's "Acceleration Corridor" with Gazley's "Continuous Flight Corridor"

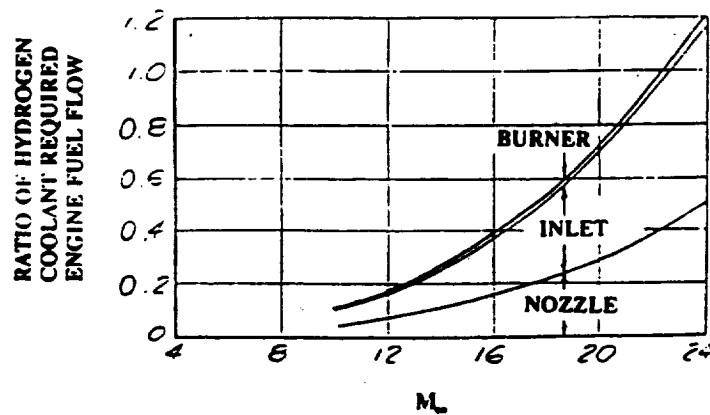


Figure 10. Cooling Requirements for  $H_2$ -fuelled Scramjet Powered SSTO Aircraft (1964)